Undersea Acoustic Communication and Navigation Technology Development and Demonstration

Final Report

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ABSTRACT

This final report contains a cumulative summary of project highlights included in the annual reports. It is provided primarily to meet contract close-out requirements, but also has a list of references and related projects. Additional information is available from the authors in addition to the published papers cited herein.

LONG-TERM GOALS

The long-term goals of this program include the development of an integrated acoustic communication and long-baseline acoustic navigation system that supports the requirements of the Autonomous Operations FNC program. The goal of the AO-FNC focuses on a multi-vehicle solution to the Undersea Search and Survey (USS) mission, in particular that proposed by Bluefin Robotics. The Bluefin Robotics approach utilizes several types of vehicles, all linked acoustically, to carry out the target search mission. The long-term goals of the overall program include the demonstration of the multi-vehicle capability for mapping, target detection and classification, reacquisition and ultimately neutralization. The acoustic communication system will enable the vehicles to transfer both navigation and target information around the network, and to allow external command, control, and mission progress monitoring.

OBJECTIVES

The objectives of the program center around the development of new capabilities and the demonstration of these capabilities on two different platforms, the Communications and Navigation Aid (C/NA) vehicle, and the Search, Classify, and Map (SCM) vehicle. The development of capabilities includes:

- A scalable modulation approach that will provide for high-rate communication at close ranges for data upload, and lower rates for long-range links.
- A synchronized transmission scheme that will provide one-way travel time measurements between the moving C/NA vehicles and the USS vehicles along with the required position information of the C/NAs which make up the moving baseline.
- Design of an efficient network for moving UUV work groups.

APPROACH

The approach to meeting the objectives defined above includes a spectrum of development, test, and evaluation tasks that are briefly outlined in this section. The participants in the program include the principal investigators at WHOI and Milica Stojanovic of MIT.

The development work includes specific tasks in modulation and signal design, network protocol design, single and multi-user receivers, and conformal arrays for the C/NA. The approach is a two-phase insertion of technology into the Bluefin vehicles. Phase one is the integration of a baseline system; phase two includes multiple incremental additions of capability as available from the development tasks of the program.

WORK COMPLETED

The work completed falls into a number of categories. We have developed a number of different hardware modules for use with the Bluefin vehicles, including internal and external modems and a conformal array module. In addition we have completed systems integration work with the Bluefin 12 inch vehicle and the 21-inch vehicle. We have developed an approach for multi-carrier modulation that is potentially suitable for variable rate multi-user PSK and carried out several data collection experiments. Additional detail for all of these topic areas is included in the results section.

The system design work was documented in a paper presented at the Oceans 2005 conference in Washington, DC [1]. The signal processing work was also presented at the same conference [2] and now submitted to the IEEE Journal of Ocean Engineering.

C/NA Array Performance Experiments. During 2006 we performed an experiment to determine the difference in receiver performance possible for several different array configurations. The goal of the test was to provide information that could be used to optimize hydrophone placement in a 21-inch vehicle. The performance of the different array configurations is described in the results section.

High-Frequency Data Collection and Communications Signal Processing. During the current year we carried out an experiment to collect data for development of broad-band multi-user acoustic communications. The test was done in conjunction with a high-frequency acoustics tests conducted by SAIC (Mike Porter) and SACLANTCEN (Finn Jensen), who invited Dan Kilfoyle (also SAIC) and WHOI to participate with a focus on Kilfoyle's spatial modulation work. We took advantage of this test to send and receive waveforms designed by Milica Stojanovic (MIT) specifically for the multi-user communications work being done for the AOFNC. The test was done in October 2003 aboard the R/V *Alliance* near Elba, Italy. One of the two candidate receivers is shown in Figure 1. This receiver includes a combiner, fractionally-spaced feed-forward filters, and a symbol-spaced feedback filter. The filters are updated at the symbol rate that lowers the computational complexity, but also the tracking ability. Use of the algorithm and its performance are discussed in the Results section.
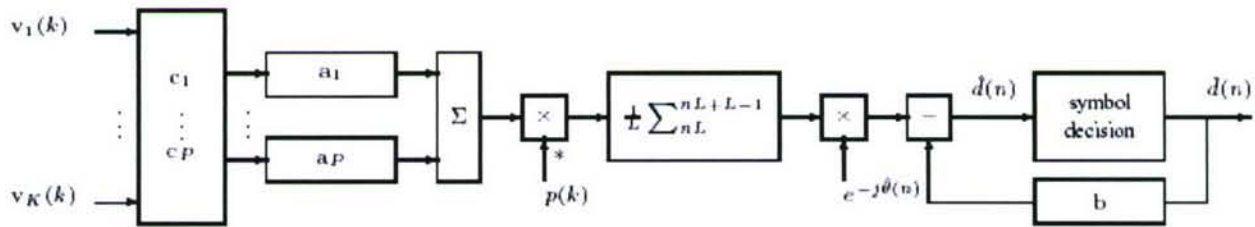
Figure 1. Multi-channel many-to-few receiver block diagram.

RESULTS

Modem Hardware for 12-inch Vehicle. An initial version of the modems for the 12-inch vehicles was fabricated and provided to Bluefin for integration and vehicle testing. Of importance for initial testing are vehicle self-noise, transducer placement, and related issues. Figure 2 shows the final version of the HF transducer with hydrodynamic faired shape using two ceramic rings (left), and the self-contained acoustic modem package used for the 12-inch vehicles when mounted externally (right). Both types of modems, bare and packaged for external use, were provided to Bluefin for integration into the 12-inch vehicles. The beam pattern of the transducer as mounted into the lower portion of the Bluefin12 foam pack was measured in a test tank also.
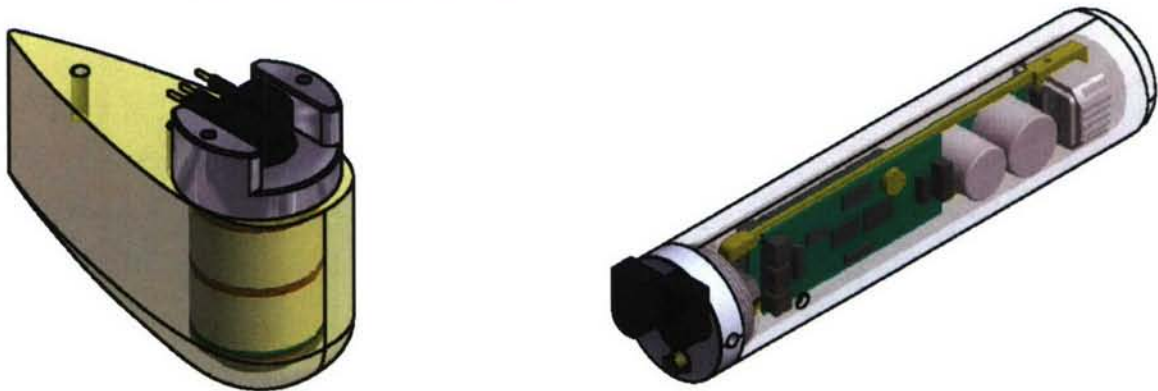

Figure 2. Left: Final version of the transducer. Right: Complete modem for 12-in AUV.

The C/NA modem is as shown in Figure 3. The modem includes different transducers for the two different bands, both for transmit and receive. The primary interface to the modem is via one connector that contains power, one serial port, a pulse-per-second signal and Ethernet. The Ethernet connection is used with a serial to internet protocol (IP) server that reduces the number of wires that are necessary to connect the different modems to the AUV control computer in the stern. Only one serial port, that of the primary HF modem, is hard-wired. The others (including the Iridium modem) go through the serial to IP server.

Comm/Nav Aid Communications System. The C/NA modem is a sophisticated assembly, which contains several different sub-systems. The core high-frequency modem controls the transmit/receiver transducer shown in Figure 2, (left), and performs the synchronized transmission of communications signals that will be used for range estimation also. A pair of multi-channel HF modems, one port, one starboard, are used for high data rate upload from the other vehicles in the work group. The final modem is for the medium frequency (<5 kHz) back-channel to Navy vessels equipped with the communications system developed for the BSY-1 sonar on the 688 class SSN and the 53C sonar on the Arleigh-Burke destroyer. The MF modem transmits using the projector shown in Figure 4 and receives on a line of elements that will be placed on the interior of the vehicle along the keel. The C/NA modem assembly is shown in Figure 3. The left side of the system contains the modem hardware, while the right contains the Iridium terminal, serial to Ethernet interface converters, and power supply. The blind-mate connection in the middle allows easy disassembly for bench testing and system integration. The entire assembly was designed so that it fits into the payload area on the 21-inch Bluefin AUV in place of a Klein sidescan package. Future versions could be designed to be modular payloads on WHOI or Bluefin 12-inch vehicles.
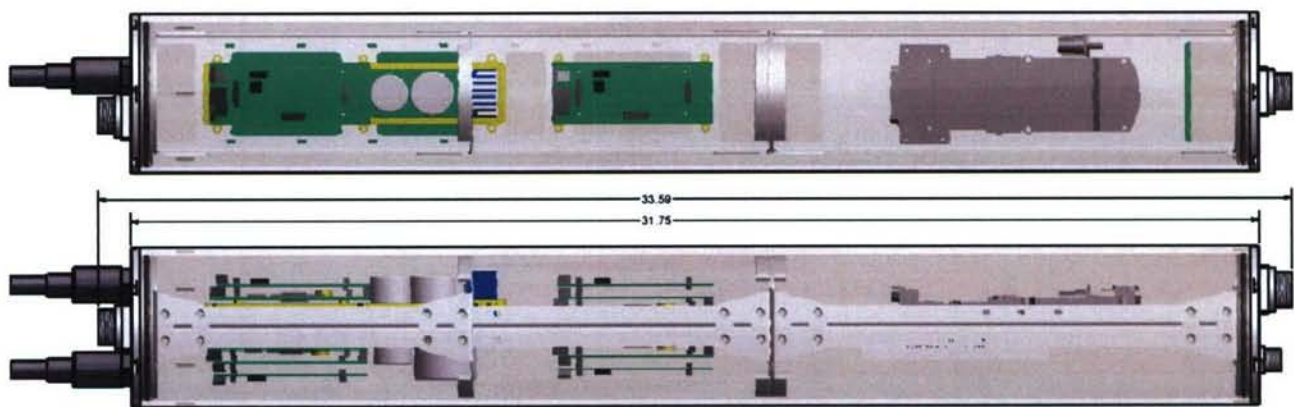

*Figure 3. Comm/Nav Aid Vehicle Acoustic Modem Assembly.*

HF Receiver Arrays. The arrays are located in the nose and are positioned to have the broadest field of view possible. The individual elements, which are made by MSI, include a small piece of active material, a piezo-composite, bonded to a steel backing plate. The steel backing removes the necessity for an air volume to the rear of the active element and reduces the likelihood that objects (air-filled or not) to the rear of the element will change the beampattern after installation. The position of the arrays and their orientation is shown in Figure 4. The medium-frequency transducer, and EDO model 6969-

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3500 is located in the center. On both sides of the MF projector are four HF elements, two aimed slightly forward, the other two aft. This increases the horizontal coverage to approximately 270 degrees. There will always be an area aft that will be difficult to cover because of the air-filled volumes in the vehicle.

The horizontal beampattern of the transducer is as shown in Figure 5. The response narrows slightly with respect to frequency as expected, but even at 35 kHz it is approximately ±45 degrees. The -6 dB points have a full ±60 degree field of view, which when combined with the forward and aft-pointing angles of the elements, maximizes overall coverage. The frequency response of the elements is very good and flat from approximately 10 to 40 kHz.
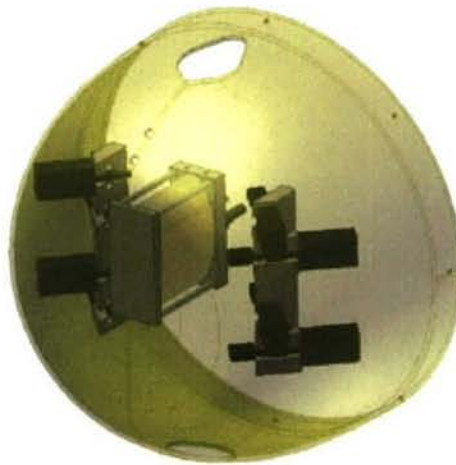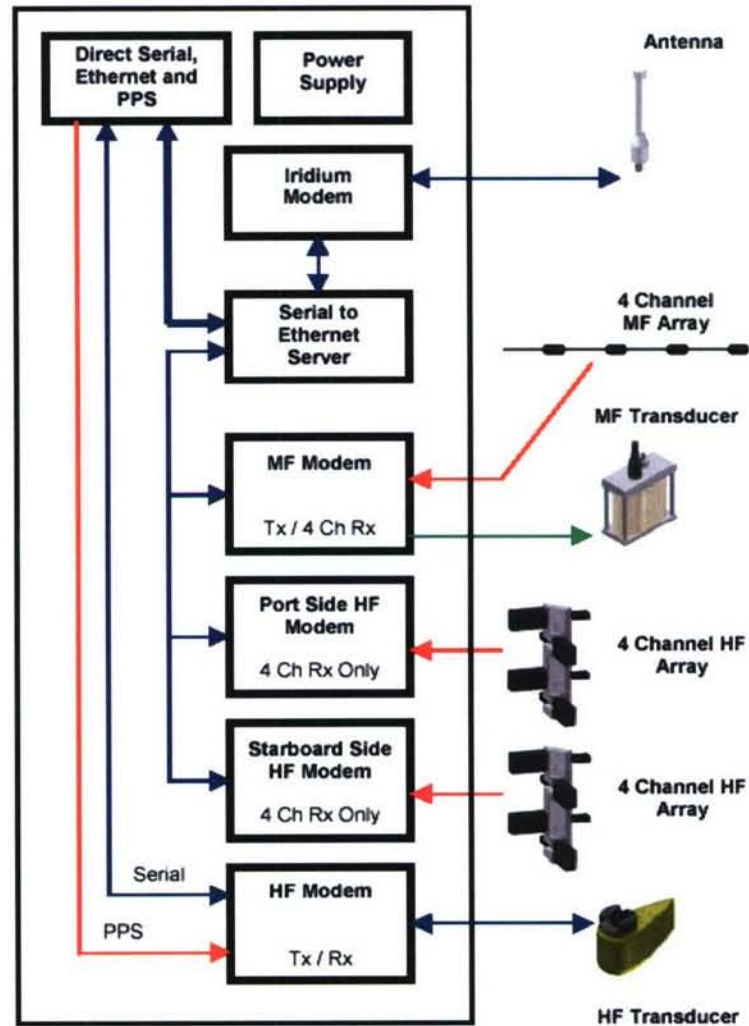

Figure 4. Nose arrays in Comm/Nav Aid
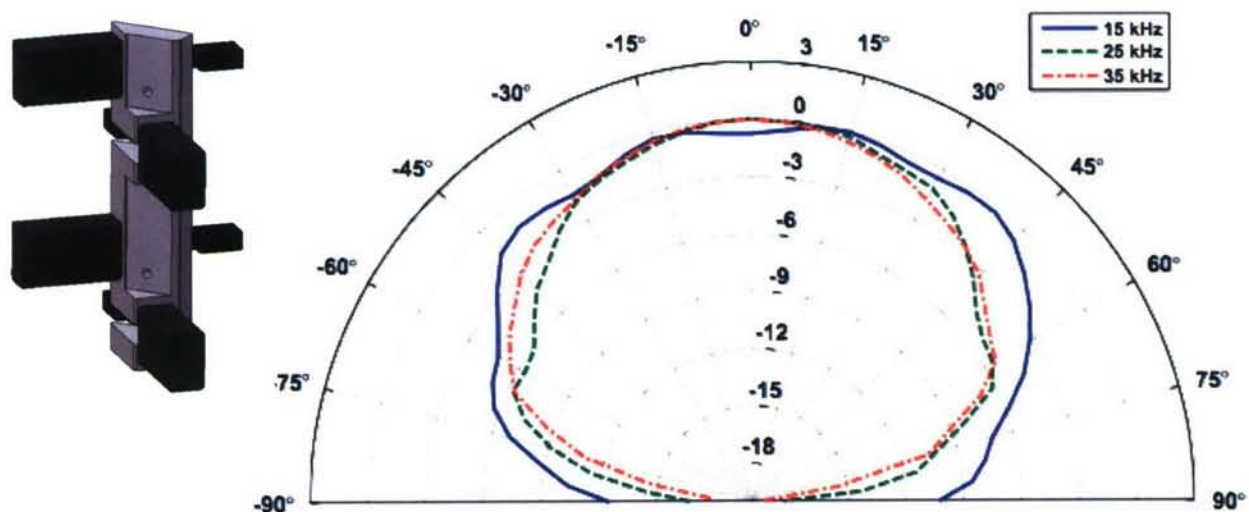
Figure 5. HF Array element horizontal beam pattern

Figure 6. C/NA Block Diagram

Synchronous Navigation. In 2005 we developed a methodology for performing synchronous navigation. This year we have implemented it and performed initial testing. Navigation broadcasts are made by the C/NA vehicles using the interoperable FH-FSK format.

In addition, the data format of the C/NA message uses the Compact Control Language specification developed and published by WHOI for AUVs [3]. This design provides a scalable framework in the physical, data, and application layers with as much 'open' design as possible so as to enable inter-operability with other systems that conform to the same basic framework and use the specified formats and interfaces.

In 2004-2005 we developed a methodology for performing synchronous navigation. This year we conducted additional tests of the system using the WHOI SeaBed vehicle, and assisted MIT and Bluefin in other tests using kayaks and vehicles. Navigation broadcasts are made by the C/NA vehicles

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using the interoperable FH-FSK format. In addition, the data format of the C/NA message uses the Compact Control Language specification developed and published by WHOI for AUVs [3].

This approach to navigation requires accurate clocks such as the one that Bluefin has implemented for the 21-inch vehicle. A similar capability was developed for use in the WHOI SeaBed vehicle under another program. The combination of the Micro-Modem, a surface GPS and the vehicle equipped with clock and modem was used to demonstrate improved navigation using updates transmitted from a known location. Figure 2 shows time-of-flight measured by the modem on the SeaBed AUV superimposed with ranging from the surface used as ground-truth. The difference between the two is less than 1 msec. This and related work is summarized in [4].

A detailed report was written to document the way that the system was implemented. The report, entitled "Synchronous Navigation with the Micro-Modem", precisely defines the different states that the system can be in and includes the specifications for the CCL structures that contain the navigation and timing information.
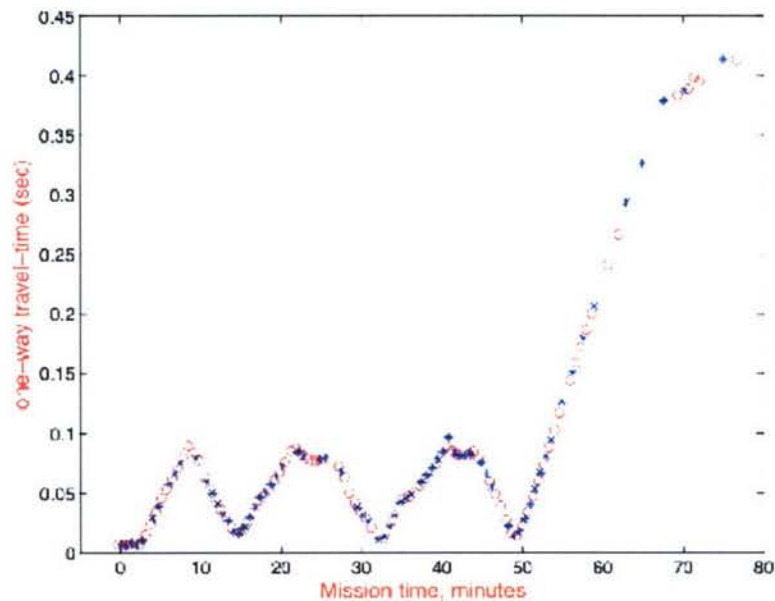

Figure 7. One-way travel times from the Micro-Modem. In blue (+) are times reported by the modem on the vehicle. The red (o) are ranges from the surface used for ground-truth.

C/NA Array Performance. The performance of an acoustic receiver using an array is governed by the diversity or beamforming gain provided by the different elements. While much discussion has occurred as to the differences between the two, the adaptive decision feedback equalizer can essentially operate in either mode, or a combination thereof, when minimizing the mean-square error at the output of the receiver. Typically the principal of diversity can be used to explain receiver performance, with highly correlated elements offering less gain than those with low coherence, which thus contain complementary information because they observe a channel with a different transfer function. Previous work has shown that the coherence is significantly less in the vertical than the horizontal, thus vertical arrays are preferred for phase coherent (and other) communications systems. While vertical diversity is readily available on moorings, AUVs offer limited vertical aperture, thus prompting the question: how much horizontal aperture is necessary to provide equivalent performance to a given amount of vertical aperture? A related issue is deciding what the best possible configuration is for a fixed two-dimensional aperture.

The results of a test, which attempts to answer the latter question, are shown in Fig. 8. The array is a 21-inch circular structure with hydrophone mounts that can be moved to create any array in the volume. Data was collected on the array, then different combinations used in the receiver. The results are shown in the lower right corner of the figure. Use of all twelve of the elements spanning both the maximum aperture in the vertical and the horizontal was the best. The remaining tests each used four elements only. Of the four elements tests, the four corners were best, as expected because it maximized array aperture. Just slightly worse than the four corners were four elements spaced vertically over 21 inches and four elements horizontal over 60 inches, with the difference between the last two just over 1 dB. The results are good: while the horizontal aperture of 60 inches is not quite as good as 21 inches of vertical, the results are only 1 dB worse, thus justifying our positioning of the array elements in a line along the bottom of the vehicle. In the future we may explore use of more vertical aperture, but space near the top of the vehicle typically contains foam flotation that can shadow elements unless they are placed outside the vehicle's shell.
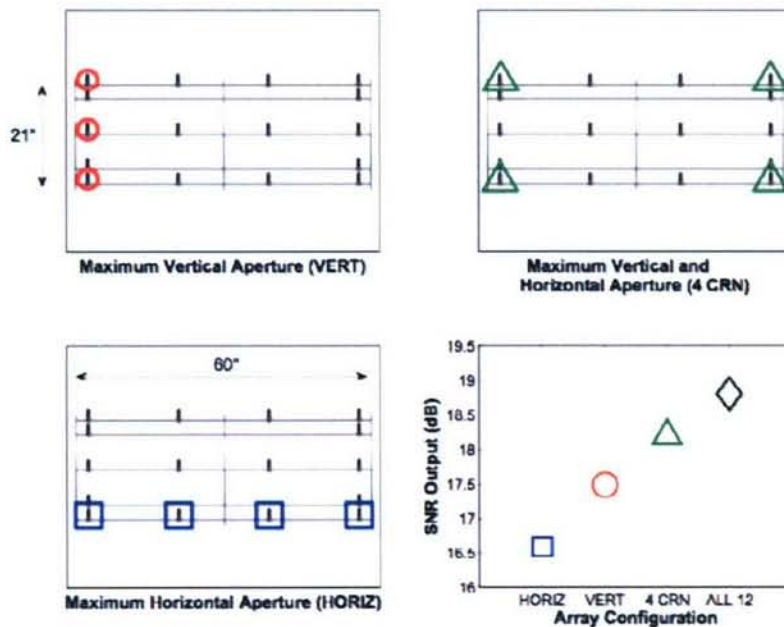

Figure 8. Array position and resulting performance.

Acoustic Communications Performance Prediction. In addition to the signal processing work performed by Stojanovic and described in previous years reports, Preisig has developed a means for estimating the performance of adaptive least-squares tracking algorithms (such as the DFE used in the acoustic modems on the C/NA vehicle). The performance of a least squares tracking algorithm (formulated as the mean squared error in estimating the value of each channel tap) can be expressed as a weighted integral in Doppler of the channel scattering function at a specific tap delay. The shape of the weighting function is itself a function of the averaging time of the tracking algorithm (lambda for a exponentially weighted RLS algorithm). Thus, the channel scattering function can be used to predict the error in estimating the channel impulse response. This impulse response estimation error can then be used to calculate the additional soft decision error that would be realized by a channel estimate-based DFE which uses the estimated channel impulse response to compute optimal DFE filter coefficients. The approach can also be used to identify the multipath arrivals that most significantly contribute to the channel estimation error, thus giving insight into the conditions that most significantly degrade communications systems performance. An example is shown in Figure 4. On the left is the channel scattering function showing channel energy as a function of time and Doppler shift. On the right is the mean-square error of the receiver as a function of time. A complete description and related analysis may be found in [5].
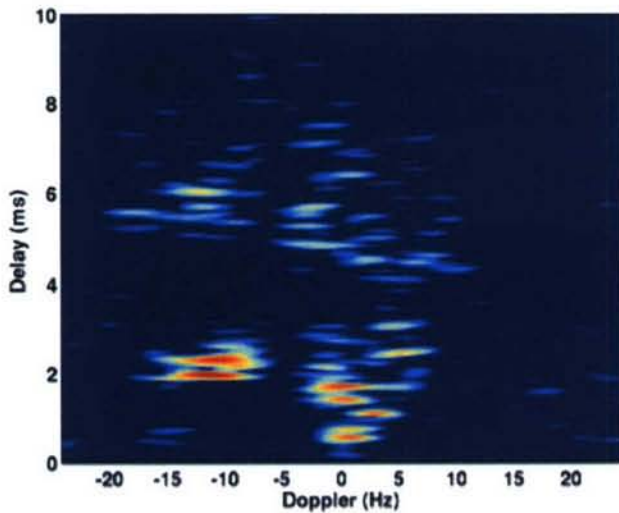

Figure 9a. Channel scattering function
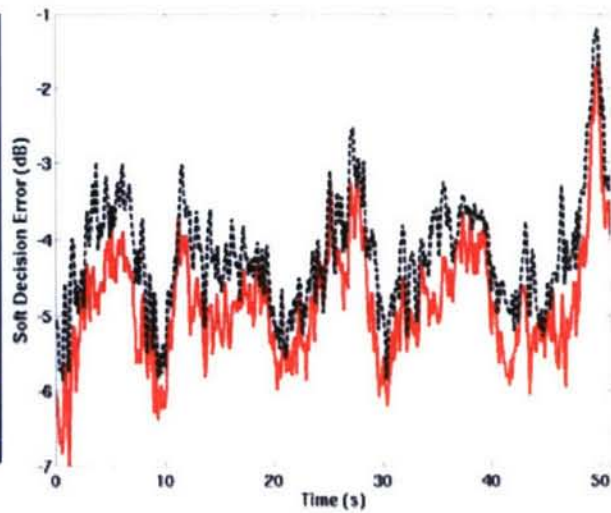
Figure 9b. Associated error from an adaptive receiver [5]

Scalable AUV Networks

Results in protocol development include a general approach for scalable networks of multiple AUVs as described in the Oceans 2003 paper by Salva-Garau and Stojanovic [6]. The work demonstrates how AUVs can communicate effectively with limited bandwidth using different multiple-access codes. The important point from this work is that it is possible to scale the Bluefin USS mission approach to include larger numbers of vehicles in order to increase survey speed. An example of clustering results with multiple work groups and code re-use is shown in Figure 10. Here five groups of two to three units are formed, each of which can communicate with nearby groups via one or more members. Code re-use is done in one instance (Code 1).
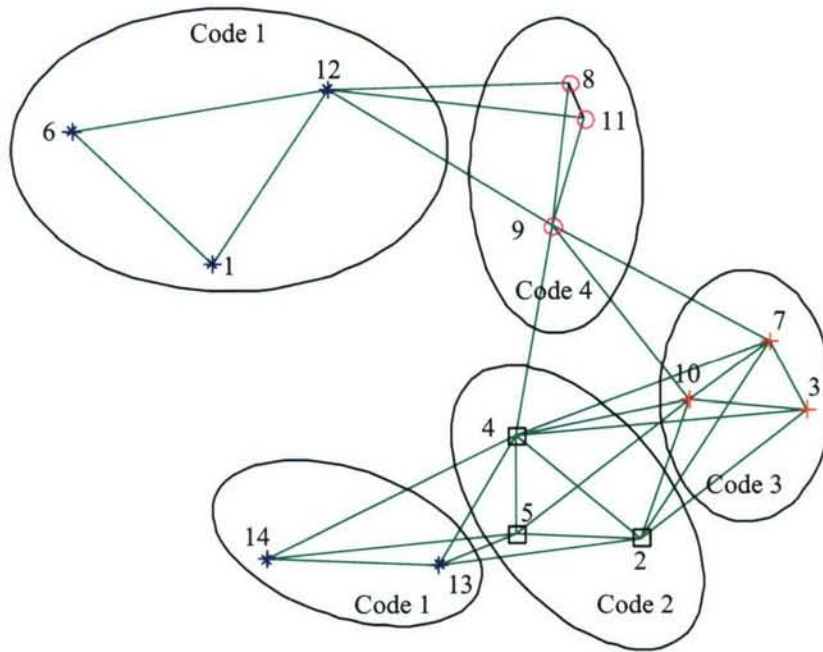
Figure 10. Results of clustering for an AUV group consisting of multiple sub-groups.

Multi-user Acoustic Communications. The data from the Elba HF test was processed using two different approaches, one of which was shown in Figure 1. The two receivers differ primarily in the means of filter updating, the requirement for which depends upon the rate of change of the acoustic channel. The signals use a bandwidth of 20 kHz, two to four times more than what we have typically used in the past. The spreading rates were 15, 63, and 255, and 4, 8, and 16 user codes were available. The data is QPSK, and the rates are thus approximately 2500, 600, and 150 bps per user. The aggregate bit rate or total channel utilization is 10kbps, 2.4kbps, and 0.6 kbps when all users transmit simultaneously. The test was done in 100 m water depth and the propagation was quite challenging, with significant channel-to-channel (spatial) and temporal variability. In spite of this, the results were quite good owing to the use of the multi-channel array.
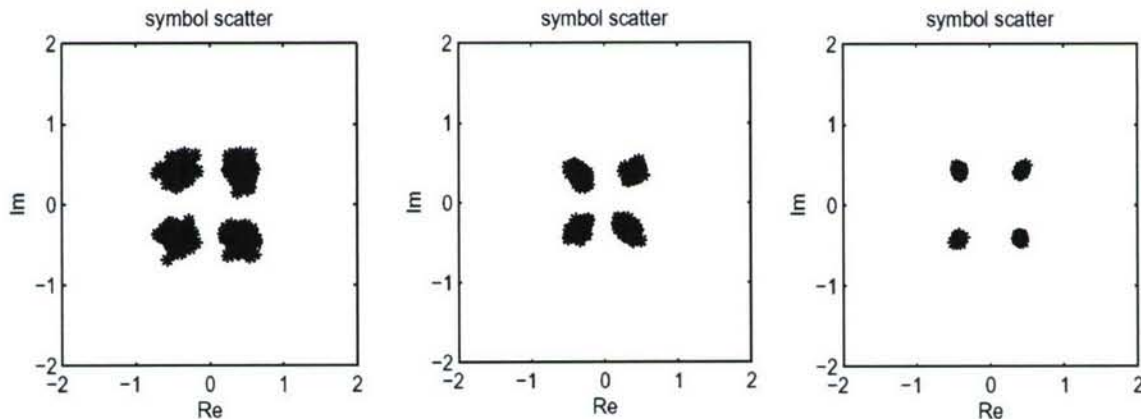

Figure 11. Chip-rate receiver performance with 15, 63, and 255 spreading .

The results using the chip-rate updating receiver are shown in Figure 11. The number of users in each case is fixed at 4. The plots show the signal constellation after equalization, with increasing SNR (tighter grouping) as the spreading rate grows (and data rate drops). The case with 15 spreading demonstrates channel utilization of 10 kHz (4 users at 2500 bps), which drops by factors of four as the spreading rate is increased. The higher spreading rates demonstrate communications that is intended to offer an acoustic signature that is as low as possible. The excess SNR in these cases is high.

Interoperability. During the AUV Fest 2005 at Keyport interoperability was demonstrated with the Benthos modem installed on an FSI solar AUV. The mode used is very similar to that which will be required to make the different C/NA systems work together. The demonstration required that the FH-FSK mini-packet be parsed as a cycle-initialization command, and then acted upon. In the test that was performed during the AUV Fest, a Micro-Modem and a Benthos modem were mounted on one of the solar AUVs. They were set to different addresses and then polled from a WHOI gateway buoy. Polling was alternated between both modems, and real data from the vehicle was sent back acoustically to the modem, then over the gateway where the CCL-encoded status messages were parsed and the information displayed for the user.

Figure 12 shows a position plot from the REMUS laptop display that includes information sent by both modems in real-time as the solar AUV was towed to different locations for testing.
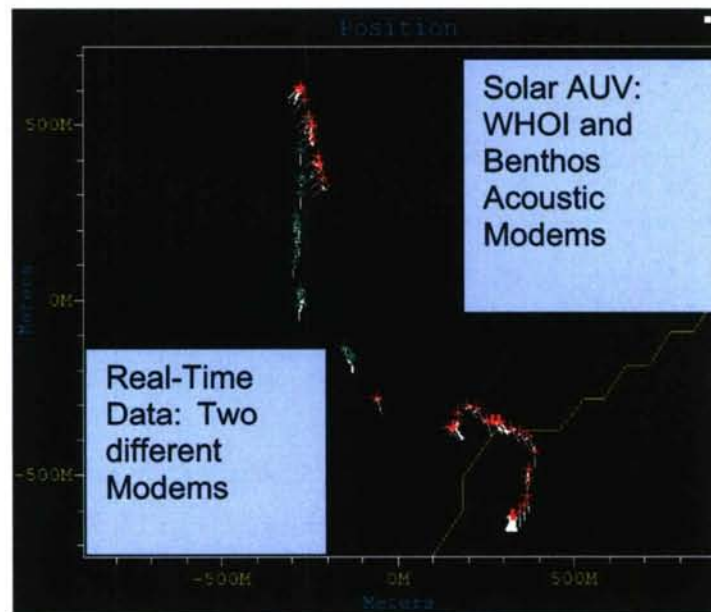
Figure 12. Real-time position from solar AUV.

IMPACT/APPLICATIONS

The impact of this work is on the Undersea Search and Survey mission, which is part of the Autonomous Operations FNC. Other applications are possible as well, in particular those similar to concepts such as the Autonomous Ocean Sampling Network and undersea surveillance.

TRANSITIONS

The most likely transition will be as part of follow-on programs that proceed to procurement or pre-procurement as the AO-FNC reaches the demonstration phase. The work performed here includes as much attention to detail as possible so that the technology may be transitioned with minimal additional investment.

RELATED PROJECTS

Acoustic Channel Modeling. WHOI (ONR). PI: James Preisig.
Acoustic Communication and Navigation in Very Shallow Water and the Surf Zone. WHOI. PI: Lee Freitag (ONR MCM program).

PUBLICATIONS

[1] Freitag, L., M. Grund, J. Partan, S. Singh, P. Koski and K. Ball, "Multi-Band Acoustic Modem for the Communications and Navigation Aid AUV," *Proc. Oceans 2005*, Washington, D.C., Sept. 2005.

[2] Stojanovic, M. and L. Freitag, "Wideband Underwater Acoustic CDMA: Adaptive Multichannel Receiver Design," *Proc. Oceans 2005*, Washington, D.C. Sept. 2005.

[3] Stokey, R., L. Freitag and M. Grund, "A Compact Control Language for AUV Acoustic Communication," *Proc. Oceans 2005 Europe*, Brest, France. June 2005.

[4] Singh, S., M. Grund, R. Eustice, L. Freitag, B. Bingham and H. Singh, "Underwater Acoustic Navigation with the WHOI Micro-Modem," *Proc. MTS-IEEE Oceans 2006*, Boston, Sept. 2006.

[5] Preisig, J., "Performance analysis of adaptive equalization for coherent acoustic communications in the time-varying ocean environment," *J. Acoust. Soc. Am.,* Vol. 118, July 2005, pp. 263-278.

[6] Salva-Garau, F. and M. Stojanovic, *"Multi-Cluster Protocol for Ad Hoc Mobile Underwater Acoustic Networks,"* Proc. Oceans 2003, San Diego, CA. Sept. 2003.

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